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Strategies for Minimizing Occupational Radiation Exposure in Cardiac Imaging

Samia Massalha [1,2,3] · Aws Almufleh [1] · Garry Small [1] · Brian Marvin [1] · Zohar Keidar [3] · Ora Israel [3,4] · John A. Kennedy [3,5]

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Abstract

Purpose of Review Radiation safety has been at the center of interest of both researchers and healthcare institutions. This review will summarize and shed light on the various techniques adapted to reduce staff exposure to ionizing radiation (IR) in the field of cardiac imaging.

Recent Findings In the last years, with the advance of awareness and the development of new technologies, there have been several tools and techniques adapted. The breakthrough of several technologies to lower radiation dose and shorten the duration of diagnostic tests associated with IR, the use of protection devices by staff members, and mostly the awareness of exposure to IR are the hallmark of these advances. Using all these measures has led to a significant decrease in staff exposure to IR.

Summary Reducing staff exposure to meet the "As Low As Reasonably Achievable" principle is feasible. This review introduces the most important strategies applied in cardiac imaging.

Keywords Ionizing radiation · Cardiac imaging · Risk · Safety

Background and Introduction

Marie Curie, regarded as one of the early pioneers of modern medical imaging, was also one of the first individuals to suffer as a result of occupational exposure to radiation. Professor Curie developed localized radiation injury to her hands and later succumbed to leukemia thought likely to have been due to repeated exposure to high-dose ionizing radiation (IR). The unrecognized oncogenic potential from high-dose ionizing radiation was appreciated later, and the new technologies of medical imaging use in far lower doses in addition to the multiple protection techniques will be discussed later.

Ionizing radiation involves high-energy particles that can displace electrons and break chemical bonds when interacting with matter. Any cell or molecule can be damaged by exposure to high-dose IR [1]. The biological effects of IR are categorized as deterministic or stochastic. Deterministic effects are measurable almost immediately or within a short latency

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✉ Samia Massalha
smassalha@ottawaheart.ca

Aws Almufleh
Aalmufleh@ottawaheart.ca

Garry Small
gsmall@ottawaheart.ca

Brian Marvin
bmarvin@ottawaheart.ca

Zohar Keidar
z_keidar@rambam.health.gov.il

Ora Israel
o_israel@rambam.health.gov.il

John A. Kennedy
j_kennedy@rambam.health.gov.il

1 Department of Medicine (Cardiology), University of Ottawa Heart Institute, 40 Ruskin Street, Ottawa, Ontario K1Y 4W7, Canada

2 Department of Cardiology, Rambam Health Care Campus, Haifa, Israel

3 Department of Nuclear Medicine, Rambam Health Care Campus, Haifa, Israel

4 Rappaport Faculty of Medicine, Technion – Israel Institute of Technology, Haifa, Israel

5 Faculty of Biomedical Engineering, Technion – Israel Institute of Technology, Haifa, Israel

period. Stochastic effects are more random in nature and are assigned a risk of occurrence over a prolonged period.

The main risk of exposure to medical radiation is the long-term risk of the stochastic effect. Examples of damage from stochastic effects are malignancies and heritable diseases in offspring [1, 2]. The extent of cellular damage is proportional to the IR exposure [3••]; this mechanistic relationship underlies the linear no-threshold (LNT) model of cancer induction following exposure. This model is the most widely accepted for purposes of radiological protection [4]. The repetitive doses of IR increase the risk [4]. While the risk to a given patient from any given imaging study is too low to be detectable and uncertain [3••], the cumulative burden may be substantial; this might be an important factor in staff exposure to IR [5, 6]. Out of prudence, the health physics community uses the "ALARA" principle, keeping radiation doses to patients and staff "As Low As Reasonably Achievable."

Cardiac diagnostic procedures account for nearly one-fifth of the cumulative radiation exposure per person per year in the USA [1, 7, 8] and approximately 40% of the cumulative dose from medical imaging procedures [9, 10•]. Nuclear cardiology is one of the most widely used non-invasive tests in assessing coronary artery disease together with cardiac computed tomography.

The indications for cardiac tests utilizing radiotracers are not limited to perfusion imaging and have been used to assess non-coronary cardiac diseases, such as systemic diseases involving the heart including amyloidosis and sarcoidosis [11, 12], infective endocarditis, and infections involving cardiac devices [13–15].

Myocardial perfusion imaging (MPI) grew rapidly over the past decades, reaching 15–20 million procedures annually. Consequently, it accounts for approximately 10% of the radiation exposure to the US population [16, 17].

A radiation employee is typically a staff member working in a medical radiation department, either diagnostic such as radiology, nuclear medicine, and interventional cardiology or therapeutic such as radiation therapy units associated with oncology departments.

Suggestions for Reduction of Staff Radiation Exposure

Education: Radiation Minimization Begins with Radiation Awareness

As the indications for radiation-based imaging techniques in cardiology continue to expand, an unanticipated consequence has been the "normalization" of radiation use in cardiology. The widening list of indications is paralleled with a plateau or a decline in radiation awareness by providers. Multiple studies indicate that cardiologists underestimate or, at times, ignore the radiation factor [15, 18, 19]. A survey of the American Society for Nuclear Cardiology (ASNC) members revealed that most participants appeared to underestimate their own radiation exposure. Consequently, only half of the responding institutions actually used one or more accepted techniques to reduce radiation exposure [1, 2]. Improving awareness is crucial to achieve the best safety measures, for example, in the catheterization laboratories. Kuon et al. showed that a brief 90-min-long mini-course in radiation safety and techniques for dose reduction was effective in a large multicenter study in Germany [20]. Other studies showed that the baseline scores of knowledge in the field of radiation exposure had increased significantly after a short training [21•, 22–24].

When resources do not permit live courses, online instruction can substitute, as this was also found to be effective in improving radiation awareness and ensuring best practices among operators [25].

Understanding that typically cardiologists worldwide have little or no training in radiation protection, the ICRP has recommended that cardiologists be formally trained in radiation protection and that interventional cardiologists and electrophysiologists should receive even higher levels of radiation protection training. Additionally, other staff who assist with fluoroscopic procedures, such as nurses, should receive radiation protection training sufficient to aid them in minimizing their own exposures. In addition to initial training at intake, staff should receive regular retraining. Such training materials have been developed and made available from IAEA (http://rpop.iaea.org) [26].

Medical staff who might be exposed to between 1 mSv and 20 mSv per year via known exposure pathways should be trained in radiation protection [27] and should be individually monitored using personal devices such as thermoluminescent dosimeter badges (TLDs).

Choosing the Right Test for the Right Patient

The awareness of exposure to ionizing radiation (IR) by the cardiology community has led to the development of appropriate use criteria to limit radiation exposure. These criteria are applied in both patients exposed to radiation during tests and to medical staff recognized as radiation employees [10•, 19].

It is of paramount importance to apply appropriate use criteria (AUC) prior to ordering imaging studies and to always weight the benefit versus the risks of a certain test [1, 3••, 28]. The imaging in Formation of Optimal Cardiovascular Utilization Strategies (FOCUS) is an initiative of the American College of Cardiology aiming for the reduction of inappropriate use of imaging by implementing the appropriate use criteria for ordering radionuclide imaging examinations. After completing all stages of the performance improvement module in this initiative, inappropriately ordered tests decreased to 5% [29].

Understanding Determinants of Radiation Exposure

To minimize radiation exposure, it is important to understand radiation sources in the catheterization laboratories, in the hot lab and after injecting a radiotracer to a patient.

The use of personal protection devices (PPDs) is necessary during the performance of fluoroscopy for interventional cardiology procedures. These include ceiling- and device-suspended lead shields, leaded or lead-equivalent cloaks and spectacles, and personal monitoring badges to monitor personal radiation dose for the staff [26]; these badges should be worn over the apron and underneath it. This is especially important considering that scatter radiation, i.e., radiation reflected off the patient, is considered an important source of hazardous exposure to providers and is difficult to shield.

PPDs are generally less effective in nuclear medicine, due to the typically higher energy, compared with X-rays, gamma ray, and annihilation photons generated by radiotracers commonly used in SPECT and PET cardiac imaging. Sources in vials and syringes should be shielded, and an injected patient should be kept at a distance (e.g., 1 m) when intervention is not required. As a general principle, when using procedures involving ionizing radiation, reducing the radiation dose to the patient also reduces occupational exposure to the staff.

In the cath lab, several factors are associated with different doses of radiation exposure; these factors include the angulation of the radiation tube, the position of the image receptor and the table, and the use of fluro rather than cine mode acquisition and dose per pulse which is predefined. However, there are some measures under the direct control of the operator and constitute prime targets for radiation dose reduction:

1. Framing rate: the number of pulses per second generated by the X-ray system. This measure is selected by the operator and ranges between 4 and 30 pulses (reflecting temporal resolution). A randomized controlled trial has shown that the use of a lower framing rate significantly reduces radiation exposure to patients and providers without a significant change to image quality or procedure time [30].
2. Field size: the area of X-ray beam that is directed on the subject. The optimal use of collimation which effectively reduces scatter radiation by avoiding outside the region of interest can also enhance image quality [31].
3. Camera angulation: Obliquely angulated camera allows beam to penetrate more tissue, by which it prevents the need for the automatic increase of the radiation dose.

Shielding

Shielding is an important method of protection against exposure to IR. These protective devices are used in the hot lab while preparing radiotracers. They are also used while injecting the tracer to the patients whether it is by using syringe and vial shields. These shields are typically made of lead, tungsten, or lead-lined steel. Ceiling-mounted shields are used in the cath lab; they are similar to the ones in the nuclear hot lab but larger, and they are usually located between the interventional cardiologist and the radiation source. Other staff members such as nurses have larger lead shields in the back of the cath lab.

The use of protective drapes The use of aprons, thyroid collars, and a protection surgical cap is essential in reducing operator exposure to IR; studies have shown 10–20-fold larger cranial radiation dose than beneath the lead shield [32, 33]. The choice of lead or non-lead aprons, the thickness of the apron, and the durability according to the manufacturer guarantee are important measures that should be considered by each institution. Aprons have different designs, some are one piece and others are two pieces including a vest and a skirt which provide a double-layer protection in the mid body and pelvis. However, the overlap double layer does not cover the left breast, and these aprons are designed for both male and female and do not account for the difference [34]. Special attention should be drawn to the fit of the apron to the health provider especially the underarm area.

Aprons should be checked annually for their quality to ensure there are no cracks. They should also be kept unfold and handled with care to keep their integrity.

Thyroid collars should always be worn, and there should be no gaps between the edge of the collar and the apron. These collars should also have an annual quality check.

Since most of the IR the operator is exposed to in the cath lab is the scattered X-ray beam after contact with the patients. This scattered radiation can be minimized by the use of completely shielded catheterization tables or the use of disposable non-lead shields placed on the patient between the image intensifier and the operator such as the RADPAD [35]; this shield has been shown to significantly reduce scattered radiation to the operator [36].

Shorter Exposure Time

The total time an employee is exposed to radiation is crucial in the cumulative amount of radiation which eventually is what counts in calculating the risk of developing radiation-related diseases. Longer coronary artery angiographies and other percutaneous procedures in the cath lab are the consequence of complicated cases. For example, at present, increasing numbers of valvular treatment procedures are performed. Good planning, applying AUC, and rotating staff to "share the dose" are good strategies for reducing occupational exposure.

As for nuclear cardiology, applying stress-first protocols reduces the time of exposure to half, while also reducing the amount of radiation.

Distance Between Employee and Radiation Source

Increasing the distance between the employee and a radiation source is an immediately effective way of reducing exposure to radiation. Doubling the distance from a physically small radiation source reduces the radiation exposure to one-fourth of the original dose. According to the following formula:

$$I_2 = I_1\ [d_1/d_2]^2$$

I_2, I_1 intensity at d_2, d_1
d_2, d_1 distance to source

This equation is roughly valid, for example, with respect to the focal spot within an X-ray tube or to a syringe containing a radiopharmaceutical. The true distribution of the external radiation field from a radiographic scanner or from a radiotracer-injected patient is more complex, but maintaining distance from a source of ionizing radiation is an important strategy in reducing occupational exposure.

While the ability of the staff to maintain distance from the radiation source in a catheterization laboratory is constrained by the requirements of fluoroscopic procedures, less apparent paths of exposure to the cardiologist can exist. A recent study has shown that cardiologists and echocardiographers performing transthoracic echocardiography (TTE) immediately after myocardial perfusion imaging (MPI) scintigraphy are exposed to radiation that might warrant monitoring. It was found that adopting left-handed TTE techniques that increase staff-patient distances can minimize the degree of occupational exposure [37].

The Use of Up-to-Date and State-of-the-Art Technologies

New technologies implement either new hardware and/or software for improved image acquisition and reconstruction, such as iterative reconstruction in both nuclear cardiology and cardiac CT angiography [38–40]. These new technologies' algorithms of resolution recovery and noise reduction result in sharper images and higher contrast. These software can be installed in an existing scanner and help reduce radiation [41]. Some protocols now have doses that are comparable to natural background radiation [42–44].

New solid-state gamma cameras using cadmium–zinc–telluride (CZT) crystals provide compact direct-conversion detectors without the need for bulky photomultiplier tubes. This facilitates flexible geometries that increase camera efficiency [45, 46]. While focusing on the heart only with their improved count sensitivity, they provide four- to seven-fold higher sensitivity compared with standard NaI-based Anger cameras [47, 48]; this translates into a significant decrease in IR dose to half dose or even lower as well as shorter acquisition time [49]. A 2-mSv study can be achieved. Acquisition of PET images in 3D mode doubles signal detection and therefore enables dose reduction to half dose [50].

In the cath lab, the use of real-time image processing chain and noise reduction algorithms can reduce up to 60% of the radiation dose without the need to prolong the procedure or affect image quality [51].

In the cath lab, the use of advanced real-time image noise reduction algorithms enables reducing the radiation dose while keeping the image quality unaffected.

Study Protocols

According to the population of examinees (low pretest probability non-obese), a stress-first protocol may be performed to reduce radiation exposure to both patients and staff. Using a regular rest-stress study protocol, the dose administered to a patient is 3-fold the dose used for a stress-first/only protocol. Applying a stress-first protocol may result, in a large patient population fraction, in a subsequent decrease of staff radiation exposure by 40% [10•, 52, 53].

The radiopharmaceutical used plays an important role in the injected dose, 99mTc agents are preferred over 201Tl due to their shorter half-life, allowing for a reduction in a factor of 0.5 in effective dose besides its superior images.

Multidisciplinary Team

While education is crucial to all departments with staff that could potentially be exposed to IR, the presence of skilled medical physicists in the professional team is of paramount importance. The performance of medical physicists has a significant impact on the quality and safety of imaging departments. They must be qualified with academic knowledge, professional skills, and competency in order to be able to perform their duties efficiently [54].

Medical institutes and hospitals should apply additional safety measures to the radiation exposure reduction field, room safety, such as suitable location of the department and rooms, special warning signs, secured doors and entrances to radiation areas, designated washrooms for patients and staff, and education. In addition, periodic inspection of all the safety measures and durability and functionality of instruments and also holding educational courses should be applied.

Conclusions

While the link between low-dose radiation and malignancies is uncertain per single study, the cumulative long-term dose medical staff might be exposed to warrants careful monitoring, and protection techniques should be applied. The target annual occupational effective dose should be kept below 10 mSv.

Compliance with Ethical Standards

Conflict of Interest Samia Massalha Aws Almufleh, Garry Small, Brian Marvin, Zohar Keidar, and John A. Kennedy declare that they have no conflict of interest. Ora Israel reports being a consultant for General Electric Healthcare.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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